MOAI MOVE – A STUDENT DESIGN PROJECT AT MIT

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Introduction

Civil Engineering students at MIT take a so-called capstone course in their last (senior, spring) semester before graduating with a Bachelor of Science in Civil Engineering. This course, entitled "Civil Engineering Design," is intended to use the students' knowledge accumulated over their time at MIT to work on and complete a number of design projects. Usually there are three such projects: one is a planning-design "paper" project dealing with local (Boston area) transportation; another is the design and actual building of a 10 foot long footbridge which can be quickly assembled. And finally, there is a so-called conceptual model project in which the students are given (or select themselves) a reasonably complicated engineering problem and prepare and demonstrate a solution using a model. While in earlier years the conceptual model involved the demonstration of physical principles underlying different buildings and building structures, the topic in the springs of 2004 and 2005 was the "Moai-Move." Several reasons led us to do so:

- It is one of the great mysteries and thus attractive to inquisitive minds.
- It involved a combination of physical, social and environmental issues – exactly what civil engineers have to deal with.
- Dr. J. Loret (Long Island) approached the author about this problem and was very enthusiastic about involving students.

This article describes the student project that begins with a summary of the task description as it was given to them; an overview of all ten projects; this is followed by a more detailed description of projects which show solutions that are quite different from the usual and/or are particularly well developed. Conclusions address the educational experience and also makes some comments about practical consequences.

The Task

Students were introduced to the history of Easter Island and the *moai* in particular in a two-hour introductory session in which also the movie "The Easter Island Puzzle," by Lanseair Productions was shown. In addition, they were given a list of references that provided background material ranging from overview-type papers to detailed descriptions of *moai* transport and attempts to reproduce how the *moai* moved. It was pointed out to the students that some of the literature is controversial and by reading it they became aware of the fact that there are contradictions. This, together with the "mystery" aspect, clearly made it a fascinating problem.

In order to provide some common ground, the students were also given a handout in which the Easter Island history was summarized and some common knowledge behind the *moai* and the *moai* movement was stated (the following is an excerpt):

> The average *moai* is about 4 m tall and weights 12.5 tons, but some are much larger and heavier. They are made from volcanic tuff. In their final position, they are placed on an *ahu,* a platform, and have a cylindrical hat or headdress made from scoria, called *pukao*, on their head. Evidently, some had eyes made from a combination coral/basalt insert. At the time of European discovery, practically all of the *moai* originally on the *ahu* had been toppled and it is assumed that this happened during the civil war of the late period. It is possible that tsunami also contributed to the toppling. Most of the *moai* still upright were near the quarry but overburden covered most of the lower part, hence the original interpretation of "Easter Island Heads."
>
> The *moai* were carved in a quarry at the extinct volcano Rano Raraku. They were chiseled out in a horizontal or inclined supine position and attached to the parent rock by a "keel" on their back. The carvers used basalt axes called *toki*.
>
> The moving of the *moai* had to be done by people because there were no draft animals on the island. Also, they did not seem to have known the wheel. From the botanic assessments, it appears that lumber was available. Also, some theories propose that the *moai* were "walked" into their final location as one does with a refrigerator. Other theories propose transport using wooden cradles/frames, possibly in combination with wooden tracks (see Van Tilburg 1996; MacIntyre 1999).

The task as given to the students was as follows:
Your task is to think about and develop a procedure by which the *moai* were moved. You can use one of the methods proposed earlier, or you can propose something new, or a combination. You have to first do this on paper, possibly including some calculations and then build a conceptual desktop model. For the latter you will, eventually, be given some model *moai*. For your initial model trials you will be given some gypsum blocks. If you need other material (wooden rods etc.) you need to buy this and you will be reimbursed. However, please discuss first what you want do with the instructors.

You are expected to do a demonstration of your model and make a brief oral presentation. All this is to be also documented in a brief report. The report and the presentation must also contain some initial assessment about the transferability

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of your conceptual model procedure to reality. If you want, you can also include in this report other aspects of the Rapa Nui history including the significance of environmental changes.

The only additional comment about the task is that it may appear somewhat vague. This was done on purpose to force the students to define the problem more narrowly, which is one of the major objectives of this design course. Also, it is not specifically stated that the transferability to reality has to be based on calculations since MIT engineering students have learned to "automatically" do so.

THE SOLUTIONS – AN OVERVIEW

Ten solutions were developed by the student teams (three to four students each). The problem and thus the solution involve three phrases.

Phase 1: The movement of the (semi?) finished statue down the slope of Rano Raraku and its placement (standing up, placed on a sled, etc.) for Phase 2.

Phase 2: Transport to *ahu*.

Phase 3: Placement on *ahu* (including placement of the *pukao*).

While all three phases were examined, the students usually put most of their effort and detailed modeling into phases 2 and 3. In their reports, the students reviewed the literature that usually included other references in addition to those given to them. Most of them reviewed the approaches suggested or tested in the literature and did so more or less formally. Below is a table providing such an assessment by one of the student teams:

Other facts gathered from the literature and relevant to deriving solutions were:

The backs of the *moai* are very often rough, indicating that at least the initial movement near Rano Raraku involved sliding of the statues on the natural ground.

The traces of old paths on the island indicated that they were used for moai transport.

At the time of *moai* sculpting and transport, there were still relatively extensive forests providing lumber for transport structures and possibly some lubricants (palm oil for instance).

One of the often-mentioned methods of *moai* movement is the "refrigerator analogy" which would lead to rounded bases of the moai. Although Heyerdahl mentions such shapes, they can, in general, not be seen. Evidence from the literature such as the tight fit of the *moai* bases to the differently shaped *ahu* indicates that the bases may have been reworked before erecting the *moai* on the *ahu*. Also, the fact that many *moai* show a re-sculpting of the "arms" to higher locations[1] may have been caused by the need to cut off the base.

As mentioned at the beginning, the "Easter Island" project is a design project. This means that solutions are developed for the given boundary conditions and other information, necessary analyses are conducted and finally the solution is built, often first in form of a prototype. These three steps are:

Developing solutions involves identifying criteria that

Table 1. Possible Moai Transportation Methods

Method	Author	Manpower	Speed	Description
I. Dragging on Y-shaped sled	Heyerdahl (ca. 1950)	180	-	- Much energy is dissipated in friction. -There is a suggestion dragging with lubrication. But the quantity required is a major difficulty.
II. A-frame step-swing	Mulloy (1970)	90	-	- Cut friction losses dramatically. - Two or more A-frames remove all friction losses.
III. Horizontal pivoting	Adam (1988)	-	-	- Work better for long self-supporting objects. - Most Moai are a little blocky, so platform of logs may be needed. - Big trade-off between positioning pivot point are available forward motion per swing and balancing the load.
IV. Upright rolling	Love (1990)	25	20 m/min	- Disadvantages of instability and the need for complex platform when transport over rocky or deformable terrain. - Statue is minimally stressed.
V. Horizontal rolling	Van Tilburg (1994, 1998)	60	Failed	- Stable but still has roadbed problems. - Requires a log track, but no trunks are strong enough for this kind of task.
VI. Levered sliding	V. R. Lee (1998)	25	30 m/day	- Instead, a sled is slid on lubricated logs - Driving force is applied by levers rather than ropes
VII. Walking, w/ropes	Pavel (1990)	15	100 m/day	- Tilt and swiveling an upright statue with ropes. - Requires precise coordination of 2 groups (4 groups to take advantage of the pendulum rocking) - May quickly spall the bottom corners of Moai - Stability and center of gravity
VIII. walking, on rocking foot	MacIntyre (1999)	8	150 m/hr	- Rocking foot or timber rig. - Offers fastest and easiest transport

[1] Editor's note: there is only one *moai* with re-carved arms, at Ahu Huri a Urenga. The reason for the re-carving is not evident and we see no evidence of any cutting off at the base.

have to be fulfilled and the (engineers') approaches to fulfill the criteria. The criteria can be technical, social or both. In the *moai* transportation case, most criteria were technical but social ones (*moai* have to stand upright during transport?!) can also be included. The technical criteria (location of origin and final location, size and shape of the *moai*) can be reasonably well but not completely defined. Given that many solutions are possible, one needs to compare and evaluate possible solutions before choosing a set of alternatives or a single final solution. This is done with so-called screening (Table 2) and scoring (Table 3) matrices as shown below for one of the teams. In the screening matrix, one compares which solution is better (+) or worse (-) in fulfilling the particular criterion. In the scoring matrix, ratings are assigned to each solution. One could also weigh the criterion, i.e. give more weight to one criterion compared to others; this was not done here. Another way to compare solutions is with a decision matrix as done by another team and shown in Table 4.

At this point it is important to emphasize that the development of solutions and their evaluation is characterized by the "open-endedness" of the problem. In other words, several solutions are possible and no one is "the best." This is very characteristic of many design problems in civil engineering and of the *moai* movement. For this reason, it is an ideal learning exercise. (Clearly this design decision process will or should, however, identify solutions that are definitely not workable.)

Following the development of the design concept is the preparation of sketches/drawings with the appropriate dimensions and the associated analysis. This was a bit complicated in that the dimensions had to be found for the model, i.e. statues of about 20 cm height, but then had to be scaled up to reality for the analysis. Some detailed sketches and analyses will be shown for specific solutions in the following section of this article. In this section, it is sufficient to mention that the analysis usually involved the following:

Determination of frictional force

Determination of pulling/pushing forces and of forces necessary to tilt the statues (if applicable)

Stability checks (limits of tilting)

Determination of stresses in timber used for frames or as levers, to check if the material could sustain the applied stressed (forces)

Special cases: e.g. buoyancy for water transport.

The ten teams came up with the following solutions:

"Refrigerator" with pulling/tilting ropes (2 projects)

"Refrigerator" with "rocking" foot made from lumber (2 projects)

Sled on track with rollers, push and pull (statue lying)

Boat

Sled or track with gliders, pulled (statue lying, with groves in back)

Levered walking platform (statue lying)

Sled on track moved by levers, as proposed by Lee (1998), (statue upright) (2 projects)

Some of these solutions will now be described in more detail.

Moai Upright on Rocking foot – Moved by Refrigerator Movement.

The photo in Figure 1 shows this concept and the students explain as follows:

To create our model, we utilized rope and curved branches that we searched for outside. We formed the rocking foot with four pieces of wood; two long pieces which were exactly 3 times the statue's height serve as the lateral braces, and two shorter pieces which were used to prevent forward

Table 2. Screening Matrix

Criterion – Solution	Labor	Materials	Speed	Adaptability to Terrain	Safety of Statue	Transport onto Ahu
Walking – Ropes	+	+	+	-	-	-
Horizontal Rolling	-	-	-	-	+	-
Walking – Wooden Rocking Foot	+	+	+	-	+	-
Walking – Stone Rocking Foot	+	+	+	-	-	+
Dragging on Sled	-	-	-	-	+	-

Table 3. Scoring Matrix

Criterion – Solution	Labor	Materials	Speed	Adaptability to Terrain	Safety of Statue	Transport onto Ahu	Total Score
Walking – Ropes	7	8	6	5	4	3	33
Walking – Wooden Rocking Foot	9	6	9	5	9	5	43
Walking – Stone Rocking Foot	9	7	8	5	5	7	42

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and backward tipping of the statue. We lashed these two longer pieces together at each end, creating an eye-shaped frame. These tapered and connected ends provided us with more stability for lateral tipping than two untied branches would have. We then lashed the statue to the eye-shaped lateral frame using more rope. In this facet of design and construction, we were not completely true to what would have been done by Easter Islanders during the time period in question. Rope would not have provided a strong enough connection between the *moai* and the rocking foot; instead, wooden bracing between the status and the frame would have been used to keep the status in place. The other two shorter pieces were then put in place on the left and right side of the *moai* to prevent forward and backward tipping. Large pivots were created on the front corners using rope.

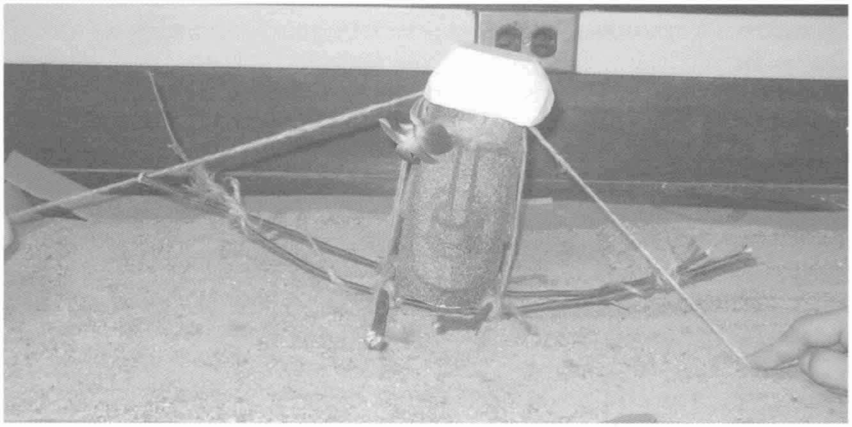

Figure 1. Moai on Rocking Foot.

This design proved to be a much more efficient version of the refrigerator-walking method. The addition of the rocking base is not only more efficient in terms of manpower and labor, but it also greatly increases the safety of the *moai* during transport. The curvature of the rocking foot allows the *moai* center of gravity to lie at a point where it can safely be tipped from side to side without toppling over. Even just a slight curvature in the rocking foot adds extreme energy savings as well as stability.

Of particular interest in these arguments is the consideration the students gave to stability:

The primary benefit of the wooden cradle is to prevent tipping of the statue. The cradle is there to extend the base of support of the structure when the statue is tipped beyond what is neces-

Table 4. Decision Matrix

Method	Machinery Required	Manpower Required	Resources Available	Topographical Feasibility	Speed	Other clues
Walking	No machinery is required, except for ropes, unless a walking platform is built to protect the base of the *moai*.	Many people would be required to move the *moai*	Rope can be made out of grasses or plants on the island.	This method would be difficult on inclined surfaces or on steep descents, especially rocky ones.	We assume it would be relatively slow to move via walking.	Island legend says that the *moai* "walked" to their location.
Sled	A sled that could be constructed from palm timber and rope. Maybe roads or trails are also needed.	Many people would be required to move the *moai.*	Palm timber and rope were readily available.	This method would be difficult on inclined surfaces, especially rocky ones.	We assume this method would also be slow, perhaps even more slow than walking.	None.
Log Roll	Palm timber would be needed, possibly notched to create a more efficient path.	Many people would be required to push or pull the *moai* along the log path, and to continually lay the logs down.	Palm timber and rope were readily available.	This method would be difficult on inclined surfaces or on steep descents, especially rocky ones.	This method would be faster than other methods, but slower on uneven surfaces.	Concerns about crushed logs and flattened surfaces from wear and tear.
Boat	A boat could be built out of palm timber and ropes.	Few people would be required for most of the trip – moving the boat through the water. More people would be required to put the *moai* onto the boat and then lift the *moai* into an upright position.	Palm timber and rope were readily available.	This method avoids most movement over island topography. The majority of *moai* were near to shore.	The main part of the journey wouldn't take very long. The standing and final movement of the *moai* would take longer. Preparation time for ship building can also be time consuming.	Most of the *moai* are located on the outer perimeter of the island.

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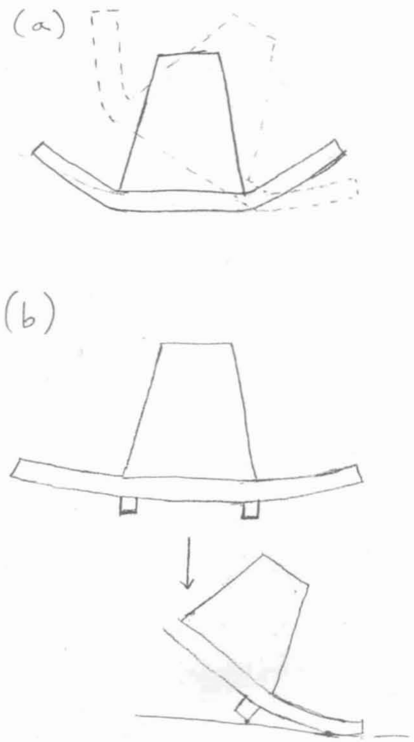


Figure 2. Schematic Showing Stabilizing Effect of Cradle.

sary for the walking motion. So, the ideal branch is one that has a high curvature at the bottom corner of the *moai*, and then decreases to no curvature as we move along the branch (See Figure 2a). That way, the *moai* pivots close to its center of mass initially but, as the contact point with the ground moves away from the statue, the weight of the statues pulls it back in. The alternative is to have less curvature (and less change in curvature along the branch), but to build up the cradle at the points upon which the *moai* pivots. This way, the pivot will stay almost exactly at the bottom corner until the cradle (Figure 2b) initiates contact with the ground at a point on the branch, causing a counter-moment to re-stabilize. In our model, we built up the pivot points in this fashion.

Moai upright – Moved by Refrigerator Movement

This solution is shown because the students, in addition to doing the analyses, ran a model experiment applying the different forces. The students first did some scaling calculations:

We estimated the average height of the *moai* on Easter Island to be about 5.8 m. From photographs of the statues, we determined the ratio of the height of the head to the height of the body to be 1:2. We used these estimations and proportions to estimate the weight and dimensions of the average moai. We also followed these proportions when creating our model as to be consistent with the full-size statues. Using these values, the model and average moai have the following attributes:

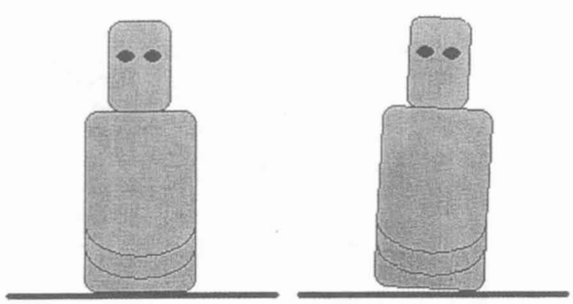


Figure 3. Tipping of the *moai*.

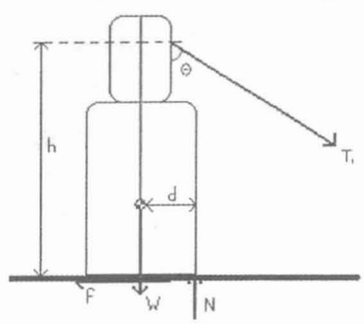
Table 5. *Moai* Dimensions – Model and Reality

Parameter	Model [cm]	*Moai* [m]
h (body)	12	3.9
r (body)	3	0.85
h (head)	4.5	1.9
r (head)	1.75	0.5

We determined the weight of the gypsum model to be 500 g by placing it on the scale. To determine the weight of the full-size *moai*, however, we estimated its volume and multiplied that by the density of stone. For a typical *moai* made of volcanic tuff (density = 1.82 ton/m^3), the average height, of 5.8 m, and the diameters of belly and head are 1.7 m and 1 m, respectively. If we assume that the ratio of the height of belly and head is 2:1, we have the height of the belly equal to 3.9 and the height of the head 1.9 m and the mass is 18.8 tons.

Finding Tipping Force: In order to "walk" the model it must be first tipped to one side Figure 3:

We determined that this "tipping" would occur when the normal force occurred only at one edge of the *moai,* i.e. the moments about that corner were 0. With this the following force diagram was in effect Figure 4:



$$W \cdot d = h \cdot T_1 \cdot \sin\theta$$

solving for T_1:

$$T_1 = \frac{W \cdot d}{h \cdot \sin\theta}$$

Figure 4. Force Diagram for Tipping.

Because both the model and the full-size *moai* have the same shape, these equations do not have to be modified to find the tipping force for the full size *moai*.

Finding Rotating Force:

While the *moai* are actually more cylindrical, we chose to approximate their horizontal cross section as a rectangle for determining the rotating force. This means that while the *moai* is tipped, all of the normal force is along one edge. Therefore, when the *moai* is rotated, the friction resisting rotation can only be along that same area. This is outlined in the diagram below.

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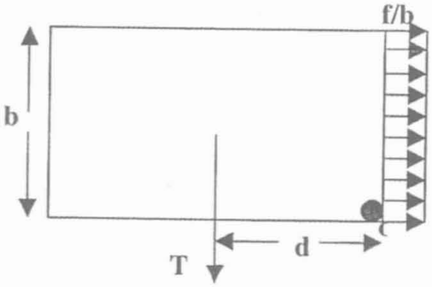
By equating resultant moment around point o to zero (Figure 5),



$$\sum M_0 = 0$$

$$T_{rot}\, d = \int_0^b \frac{F}{b}\, y dy$$

$$T_{rot} = \frac{Fb}{2d}$$

Figure 5. Force Diagram for Rotation.

where F is friction force along the edge of a *moai* base, which can be determined from the forces shown in Figure 4.

$$F = m_s N$$
$$= m_s (W + T_{tip} \cos q)$$

Because the coefficient of static friction between materials is always higher than the coefficient of sliding friction (for sustained motion), we assumed that if enough force were applied to overcome static friction, the *moai* would rotate forward. Thus:

$$T_{rot} = \frac{\mu_s (W + T_{tip} \bullet \cos\theta) b}{2d}$$

Following the procedure outlined above and using the physical parameters (Table 6) we arrived at the following forces to tip and rotate the model As mentioned above, the students then ran a number of model experiments Figures 6 and 7).

The top image in Figure 7 shows the model setup above the tabletop. The *moai* is standing vertically on a sandpaper surface, and has twine attached to its head to tip the statue, and attached to its belly below its center of gravity to make the statue advance once tilted to one side. The bottom image in Figure 7 shows our method of applying discrete increments of tension to the ropes. We attached hooks to the ends of the lines, which we loaded with washers.

Table 6. Model Parameters and Tipping/Rotating Forces.

Parameter (dimension)	Model (cm)
h_{body}	12
r_{body}	2.3
r_{head}	1.8
h_{cg}	6.4
M[kg]	0.5
Fw[N]	4.9
Tipping Force	Tipping Force
Θ	90
T_{tip}[N]	0.79
T_{tip}[kg]	0.08
T_{tip}[1b]	0.18
Rotating Force	Rotating Force
μ_s(friction)	0.4
T_{rot}[N]	1.14
T_{rot}[kg]	0.12
T_{rot}[1b]	0.26

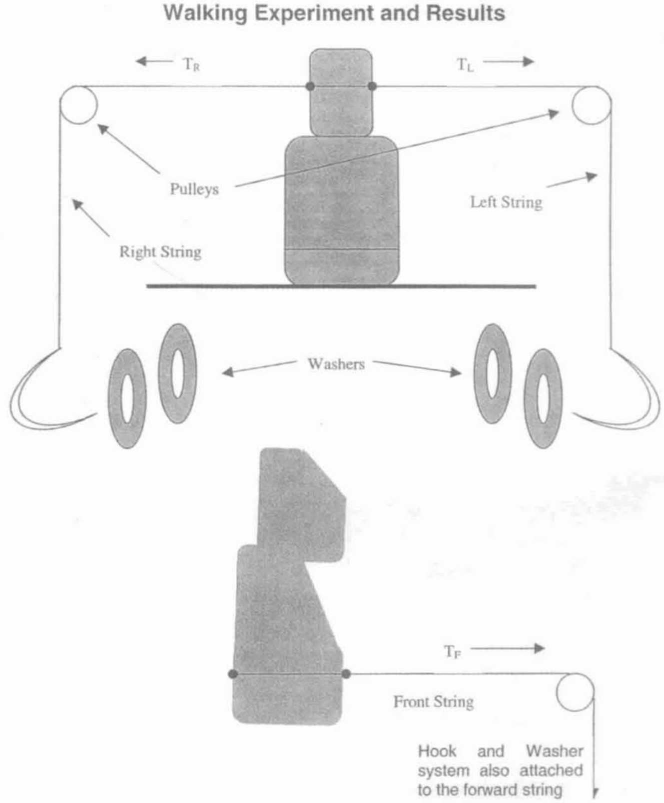


Figure 6. Model Setup for Walking Experiments.

Experimental Procedure

Suite 1: Constant T_F

1. Apply constant tension to the Front String by placing washers totaling about 75 g on the hook suspended form the Front String.
2. Place 1 washer on the Right String to provide counterweight to prevent the *moai* model from toppling once a corner is lifted.
3. Incrementally load the Left String by placing one washer at a time on the hook until the right corner lifts up from the table.
4. The tension on the Front String should be sufficient to rotate the *moai* forward around the left corner. (If it is not, add washers to the front hook until the *moai* model rotates forward).

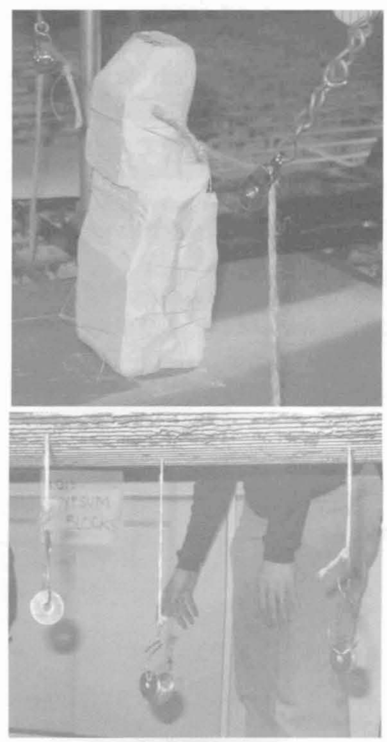


Figure 7. Table top setup above; method of applying tension to the

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5. Unload each hook and weigh and record the weight added to each string including the hook.

6. Repeat all steps for loading the Right String.

Suite 2: Constant T_R or T_L

1. Place 1 washer on the Right String to provide counterweight to prevent the *moai* model from toppling once a corner is lifted.

2. Apply constant tension to the Left String by placing washers with a total weight of T_L found in Suite 1, or just enough to lift the right corner off the surface.

3. Incrementally load the Front String by placing one washer at a time on the hook until the Moai model rotates forward about the left corner.

4. Unload each hook and weigh and record the weight added to each string including the hook.

5. Repeat all steps for loading the Right String.

We conducted the experiments outlined above with a model with a straight base, and a model with a rounded base on a steel plate and a sandpaper surface. When our set-up was configured such that the head-ropes were horizontal, the expected force to tip our straight-based *moai* model was 133 grams. The force required for the left side was 130 grams and the right side required in excess of 160 grams. We believe this was due to poor shaping of the model's foot.

At the ideal position, rotating about the left side, loading the belly rope (Front String) with 34 grams caused motion. This implied a coefficient of static friction between the gypsum and steel plate of about 0.1. When sandpaper was used as the walking surface, movement required 130 grams of weight on the belly rope, resulting in a coefficient of static friction of about 0.4. However, even in this situation, the amount of force needed for rotation was still approximately equal to the amount of force needed to tip the moai.

We also found that the *moai* with a rounded foot required substantially less force to tip and rotate. For that reason, we pursued several trials with the rounded-foot model. Following the procedure outlined above, we obtained results that are shown in Table 7.

Hence, the average tipping forces for our model *moai* were: T_F = .735 N. T_R = .70 N and T_L = .87 N. The discrepancy between the right and left tension values were due to the imperfection in the geometry of the hand carved base. These values are very close to the values predicted by our model (T_{tip} = .79 N and T_{rot} = 1.14 N) (see Table 6) and verify the credibility of the mathematical model at predicting the forces required to walk a *moai* according to our proposed methodology.

Table 7. Results of *moai* Experiments

a) Suite 1 with Rounded Foot			
Trial	T_F (g)	T_L (g)	T_R (g)
1	75	88	12
2	75	12	70
3	75	88	12
4	75	12	71
b) Suite 2 with rounded foot			
1	75	90	12
2	75	22	74

Finally, a comparison was made between model and reality: Most of the equations developed for use with our model do require only the most basic inputs. Most models suffer from problems concerning scale. For example, when a moai height doubles, if all the proportions of the moai are constant, the volume, and thus the weight, will increase by a factor of 8.

However, because the force equations developed for use with our model use height and weight separately, we do not have this problem. In addition, our model may be used for moai that do no have the same proportions as our test case, provided the dimensions can be measured.

The only difficulty in transferring our model to actual walking of the *moai* is determining the actual coefficient of friction between the *moai* and the crushed gravel roads that encircle Easter Island. However, it seems more likely that the coefficient is closer to our sandpaper test case (m_s = 0.4) than the smooth metal plate.

Scaling to the actual *moai* of 18.8 ton mass, the total force required to tip and rotate an average size standing moai are predicted to be 3900 kg and 4300 kg respectively. Assuming that one puller can pull about 70 kg. each, this process will require about 55 tippers on each side and 60 pullers in the front.

Using Water Transport

Again, quoting from the students' report:

1.The first step is to slide the freshly carved *moai* on its back down to the flat terrain by using the natural incline of the mountain.

2. Next, the natives build a boat approximately 3 meters wide by 6 meters long by 1.5 meters deep using the palm wood and rope found on the island (Figure 8). The boat can either be a solid structure or a hollow watertight vessel that is sealed by tree sap or palms. If it is watertight, the structure is built in two main sections, a deck and base, which are connected by ropes. The bottom base of the boat will have a curved bottom that forms about 30° angle with the ground when tangentially tilted to its side, whereas the top deck will be a flat surface similar to a simple raft. After shipbuilding, the moai is slid onto the boat's deck using manpower and the incline of the mountain. The *pukao* is carefully placed onto the ship adjacent to the head in this same manner.

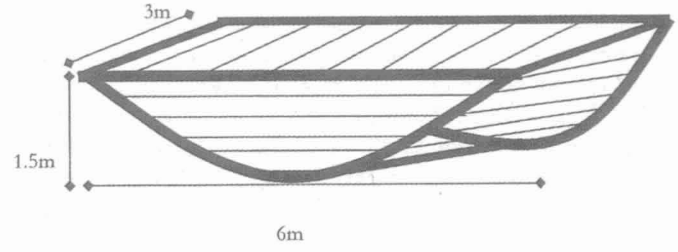

Figure 8. Schematic of Boat.

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3. Legend says that the movement of the *moai* was a grand feat that was accomplished by the collaborative work of the villagers. In this spirit of the legend, we assumed that while some of the natives worked on the boat, other men labored at digging a trench that connected the foot of the mountain to the sea. This trench measured approximately 4 kilometers long, 17 meters wide and 4 meters deep and allows the sea water to flow into it. The boat was then placed in this narrow trench and paddled with wooden oars downstream to the sea. At this point the boat is then sailed along the coastline to their desired location.

4. Once at the shore the boat is docked at the beach by having men pull the boat up onto the shore with rope. The natives then use the curvature of the boat's bottom as an aid to tilt upwards to an angle of approximately 50°. The statue, however, will start sliding downwards off the boat when the tilt is at 30° to the horizontal. The force needed to both pull the boat to shore and tilt upward is decreased by the usage of rope and a wet bottom surface. At this point, both the moai with the *pukao* atop its head is slid onto the flat terrain in a standing position. The moai will be facing inwards because of his placement onto the boat. (He was pushed onto the boat feet first and, therefore, docked onto the shore feet first.) This placement follows the islander's oral traditions and the current position of statues.

5. Finally, the *moai* is moved into position on top of the *ahu* using the "refrigerator method." The villagers ceremonially walk the movement to its final destination by pivoting the status from side to side along the flatlands that run along shore.

Again, this was built up by calculations.

Building the Boat

The boat is designed to support and transport an average-sized *moai* of 12.5 tons. Archimedes' Principle governs the buoyant force required to support the boat and statue, and is given by:

$$F_B = g_w V_{boat} \qquad (1)$$

Where F_B is the buoyant force, g_w is the specific weight of water, and V_{boat} is the water volume the boat must displace to provide the required buoyant force. Setting the buoyant force equal to the weight of the *moai* implies that the entire volume of the boat is submerged. Since some of the boat must remain above the water level at all times to prevent the moai from sliding off into the water, and to account for the weight of people who might be on the boat working with the statue, we will employ a safety factor of 1.3 to W, the weight of the *moai*. Using Equation (1), we find:

$$1.3W = F_B = g_w V_{boat}$$
$$(1.3)(25{,}000 \text{ lbs}) = 62.4\ {}^{lb}/_{ft3}(V_{boat})$$
$$V_{boat} = 520 \text{ ft}^3$$

Assuming that the inhabitants of Easter Island used palm trees to construct their boats, and that the density of palm is approximately 330 kg/m^3, the ratio, R, of material above the static water level to material below static water level is given by:

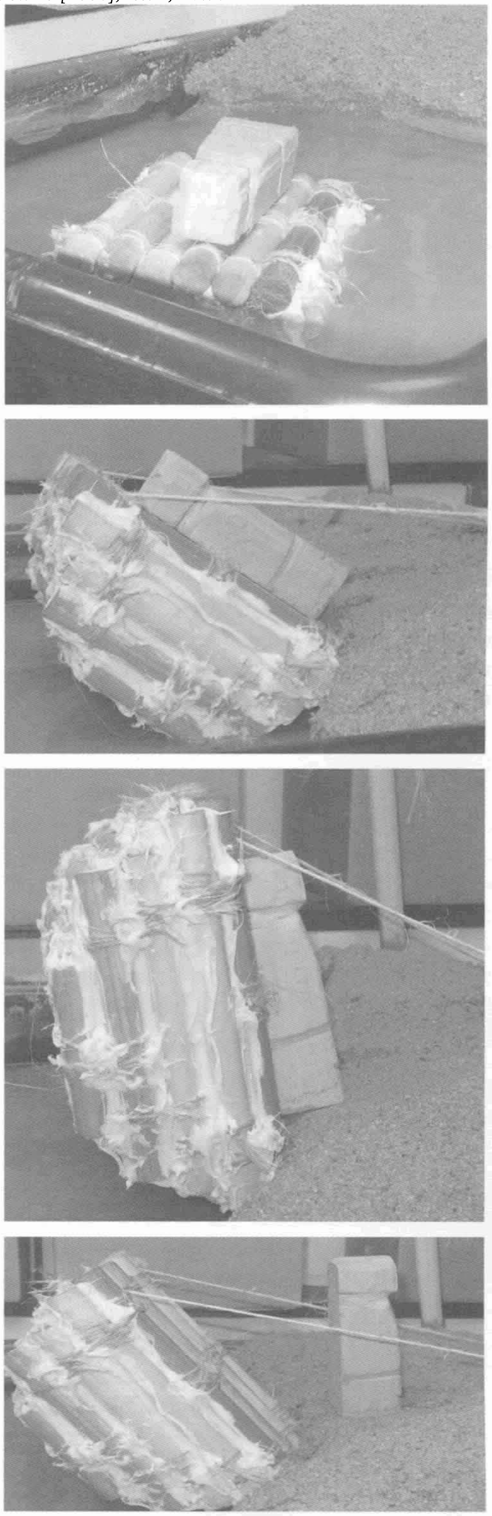

Figure 9. Photos of Boat Model.

(1) $$R = \frac{\rho_w - \rho_p}{\rho_w}$$

and (2) $$R = \frac{1000\ {}^{kg}/_{m^3} - 330\ {}^{kg}/_{m^3}}{1000\ {}^{kg}/_{m^3}} = \frac{2}{3}$$

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This ratio implies that for every unit volume of palm wood completely submerged, the effective buoyant force for supporting an additional load is 2/3 of the total buoyant force given by (1). In other words, the total buoyant force is reduced by the weight of the palm wood.

The simplest boat design is a raft of palm logs bound together in a single row by rope or reed. Combining the results from (1) and (2), the volume of palm logs, V_{palm}, required to construct such a raft is:

$$V_{boat} = R \times V_{palm}$$
$$V_{palm} = 3/2\ (520\ ft^3) = 800\ ft^3.$$

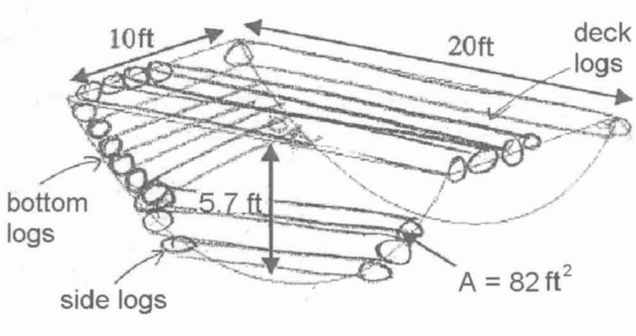
Assuming the average diameter of the palm logs is 1 foot, the raft size (in linear feet) would be:

$$\frac{800}{\pi r^2} = \frac{800}{\pi 0.5^2} = 1020 ft \quad \text{or roughly } 32ft^2$$

Since the average *moai* is approximately 15ft tall by 4ft wide, a 32ft x 32ft square raft is not practical. It is possible to reduce the surface area of the raft if the total volume is kept constant, removing wood from the deck and attaching it to the bottom of the raft can achieve this result. If we want a raft that is 20ft long by 10ft wide, the raft would need to be approximately 4 rows deep. While the size of this raft is much more manageable to use for transporting the *moai*, the construction becomes a bit more complex.

The boat alternative that we chose as a model for transporting the *moai* incorporates a curved bottom that allows the statue to be brought to its upright position once on shore. To maintain the displaced volume of $800ft^3$, the boat roughly takes the shape of a cylinder cut axially down the center with dimensions as shown in Figure 10.

Because the amount of wood required to construct this boat is less than 800 ft^3, it must be watertight, otherwise, it will sink when loaded. The assumption that the inhabitants of Easter Island had the knowledge and ability to construct a watertight boat is a reasonable one since they were on an island and needed to adapt to their environment. If for some reason the boat could not be made watertight (i.e. due to lack of waterproofing materials) the same shape and dimensions could be used to build a boat by adding 42 additional 10ft x 1ft diameter logs to the hollow center as shown in Figure 11..



# logs along bottom: 24	length of bottom logs: 10ft
# logs on deck: 10	length of deck logs: 20ft
# logs on sides 12	avg. length of side logs: 13ft

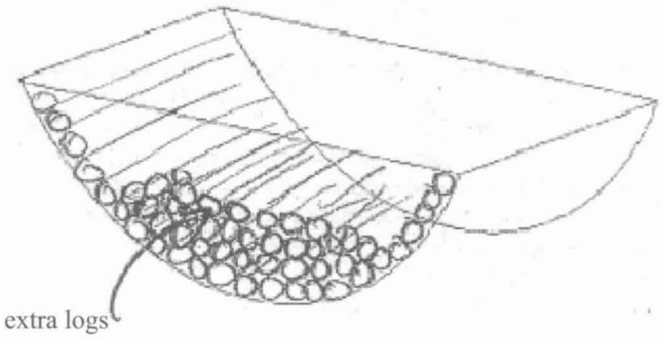
Total length of logs: 596ft Area of log cross section: . $785ft^2$
Total volume of logs approx. = 470 ft^3

Figure 10. Sketch and table of dimensions of boat.

Moving the moai from the "Boat" into land

When the boat arrived near the *moai* final destination, it was pushed as far up onto the land as possible. Ropes were attached to the *moai* so that the inhabitants on land could pull it off the boat and those on the boat could push it off. The amount of force required to move the *moai* on the surface of the boat is about 15,000 lbs.

With $F_f = mN$ (3)
N = Weight of Structure ~ 25000 lbs
m = Factor coefficient ~ 0.6



# logs along bottom 24	length of bottom logs: 10ft
# logs on deck: 10	length of deck logs: 20ft
# logs on sides 12	avg. length of side logs: 13ft
# logs inside: 42	length of inner logs: 10ft

Total length of logs: 1016ft
Area of log cross section: . $785ft^2$
Total volume of logs approx. = $800ft^3$

Figure 11. Alternative boat design with extra palm logs to compensate for being non-waterproof and table of dimensions.

As it moves, the boat tips and eventually the critical angle is reached at which point the *moai* slides off the boat on its own. The critical angle can be calculated using the calculations and illustration in Figure 12.

$$F_f = W \sin\theta$$
$$W \sin\theta = \mu W \cos\theta$$
$$q = \tan^{-1}\mu,$$
$$\text{So } \theta = \tan^{-1}(.6) = 30°$$

As the *moai* slid down, the boat continued to tip until the statue reached the ground. Even though the boat could have tipped a maximum of 60°, we assume the final angle was approximately 50° since the statue probably slid off faster than the boat could

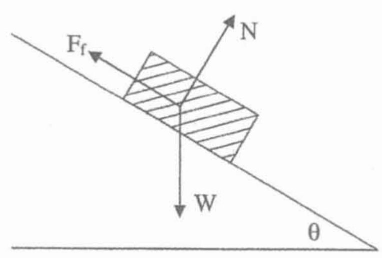


Figure 12. Force Diagram – Sliding "Uphill".

tip. The *moai* is about twice as heavy as the boat, and could have easily pushed the boat from underneath it as it slid off. To prevent the boat from sliding due to the force of the *moai*, we assume that the inhabitants placed large rocks or piles of logs behind the boat. With the *moai* and boat in an inclined position, the inhabitants then attached ropes to the boat and pulled until the boat and the *moai* reached a completely upright position. Assuming the inhabitants were far enough away to prevent getting crushed if the *moai* happened to fall over, the amount of force required to pull the *moai* upright is calculated as shown in Figure 13.

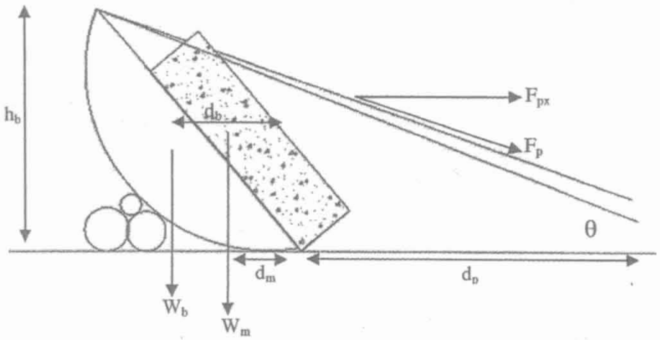


Figure 13. Schematic and Force Diagram – Tilting *moai* and boat.

F_p= the force of the inhabitants pulling on the boat
F_{px}= x – component of that force
h_b= height of the boat, 15ft
W_b= weight of the boat, ~10,000 lbs
W_m= weight of the *moai*, 25,000 lbs
d_b= distance from the center of gravity of the boat to the pivot point, 5ft
d_m= distance of from the center of gravity of the *moai* to the pivot point, 2ft
d_p=distance of the inhabitants to the pivot point, 25ft

The angle, θ, at which the inhabitants pull the ropes is equal to

$$\theta = \tan^{-1}\frac{15}{25+10} = 23^{\circ}$$

The x-component of the force of the inhabitants

$$F_{px} = \frac{(W_m \times d_m) + (W_b \times d_b)}{h_b}$$

$$F_{px} = \frac{(25{,}000 \text{ lbs} \times 2 \text{ ft}) + (10{,}000 \text{ lbs} \times 5 \text{ ft})\ )}{15 \text{ ft}}$$

F_{px} = 6700 lbs

Therefore, the force of the inhabitants pulling on the boat

$F_p = F_{px} \cos \theta$
F_p= (6700 lbs) cos 23
F_p @ 6200 lbs

It takes about 60 villagers to accomplish this task, which is reasonable.

Levered Walking Platform

The students in this team actually first considered a tripod type frame and moved this in the refrigerator mode. They concluded that the supports would not be strong enough when tilting took place. Following this, they developed what they called the supine walking method using rotation pins and levers (Figure 14):

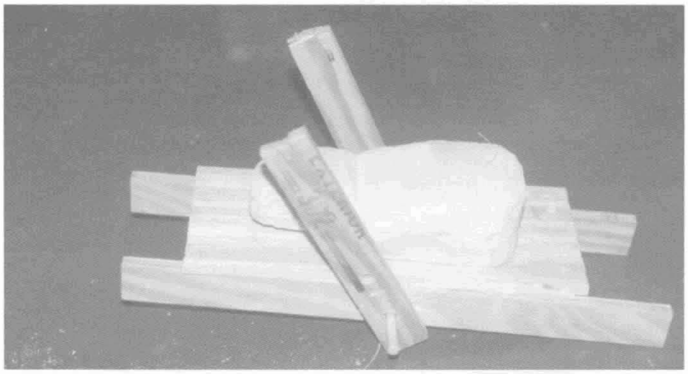


Figure 14. Resting position of supine walking method that uses a lever-pin system.

The steps we take to move the *moai* begin at the quarry where we load our platform in a tilted position with a series of rope pulleys. A pulley in this instance requires the use of ropes looped up over stumps, logs, or rocks. Once we have placed the head on our angled platform, we can lower the platform and continue our walking method by using the lever-and-pin system devised and shown in Figure 15. To increase leverage capacity, we use the outer pin-hole for walking (the inner is used for standing). To circumvent any rocks or obstacles, rotating the levers in the opposite directions to each other will turn our walking platform. Once we reach the *ahu* platforms, we return to the highest-angle position (the same as the loading position) and use rope leverage to pull the *moai* into place. In order to get the side levers into the upright position, as is needed for both loading and unloading, the people lift to their highest possible point on the inner pin hole, and then a second crew is ready, with ropes to pull the levers the rest of the way into the upright position. This places the head into an angled supine position. The *pukao* is placed using a similar rope pulley system as was used for lifting the statue out of the quarry.

Moving the Moai

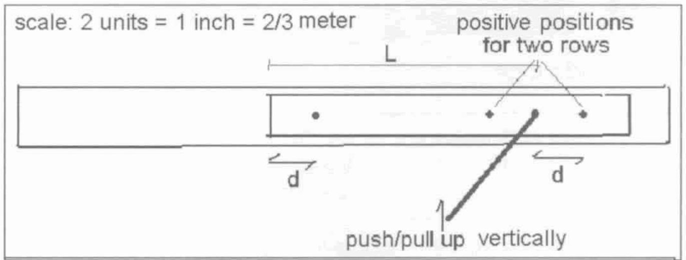


Figure 15. Our model walks.

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Calculations: Static or just when the *moai* lifts from the ground the max force required.

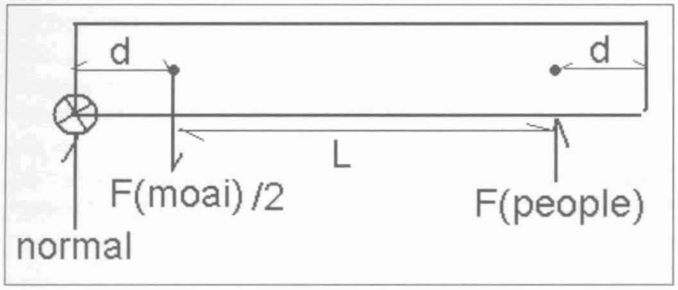


Figure 16. Forces on One Lever. (There is one lever on each side, see Figure 14.)

Moment $$M_x = -\frac{F_m}{2} \bullet d + \sum F_p \bullet \ell = 0$$

F_{moai} = Weight of *moai.* F_{people} = Force exerted by people.

$$\sum F_p = \frac{d}{\ell} \times \frac{F_m}{2} = \frac{\frac{2}{3}}{\frac{10}{3}} \times \frac{F_m}{2} = \frac{F_m}{10} = 2500$$ lbs. assuming F =25000 lbs.

So, if one person can lift 50 – 100 lb, 25 – 50 people are on each side. Using ropes to rotate the handle will reduce the force to lift after initial lift from the ground (Figure 17).

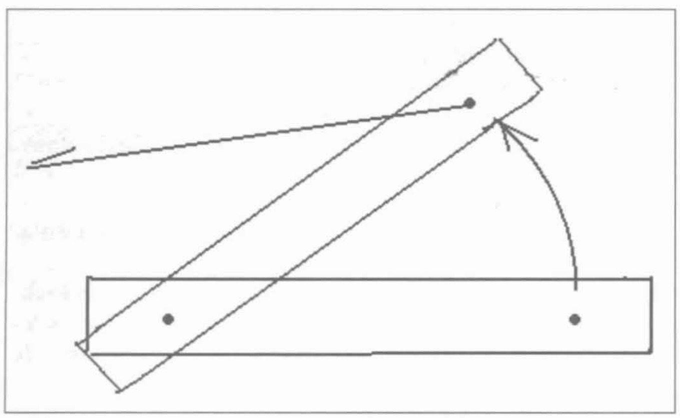
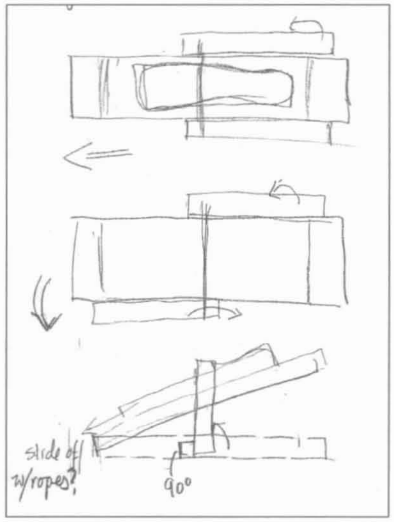


Figure 17. Lever lifting with ropes.

Conclusions

The *Moai* Move project was given to the students as a design project and they solved it accordingly by evaluating different possible solutions, choosing one or occasionally two of them, developing and analyzing the details and finally building and demonstrating/testing the conceptual model. The solutions were mostly those proposed in the literature (refrigerator walking, sled with statue in upright or prone position) but included also new ideas (rocking feet, boat lever system). In



1. To move forward. Weight should be more toward the back Lowest hole on lever.

2. To rotate. Lowest hole on lever

3. To unload: highest hole on lever and rotate to 90° head should be positioned more forward

Figure 18. Typical usages of the lever.

all cases the testing and analysis showed that the proposed concepts might work in reality. (The next steps if one were to go this route would be detailed analysis with the structures and materials proposed and then run reduced size or full sized tests in-situ.)

While the students' solution may also be a minor contribution to solving the Easter Island puzzle, the design exercise certainly fulfilled its educational goal. The students were exposed to a real open-ended problem and they conceptualized, designed, analyzed and tested their solutions. The solutions include an analytical reality check in terms of estimates of actual manpower needed. In a number of solutions, the students, in their accompanying reports and presentations, went beyond the physical problem and assessed and commented on the social and environmental conditions. On a more detailed level the students became aware of the necessity and limitations of scaling from a small model to reality. This is very important for civil engineers who usually solve problems for which actual size prototypes cannot be tested.

List of Students 2004

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Published by Kahualike, 2006